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DEVELOPMENT OF A TORSIONAL DYNAMOMETER

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ABSTRACT

This report presents the design and evaluation of a photoelectric device used for measuring the input power requirements of rotating machinery. Mechanical and electronic design considerations are presented, along with an operational evaluation of the device.

A multirange torquemeter utilizing interchangeable load shafts provides effective instrumentation of pump input power requirements for hydraulic research conducted by Intermountain Forest and Range Experiment Station in cooperation with the Department of Civil Engineering and Engineering Mechanics of Montana State University. The design is readily adaptable to other applications requiring measurement of power requirements of rotating machinery. A photoelectric principle used in the design provides:

1. Signal generation and transmission without physical contact with the shaft (i.e., no slip rings);
2. Rpm counting capabilities inherent in the design; and
3. Load range flexibility with interchangeable shafts.

Basic Design Concept

The basic design, shown in figure 1, incorporates a slender shaft mounted in its own bearings. Two serrated disks are mounted on the shaft. These disks interrupt the light beam passing between each of two sets of lights and photodiodes, thus producing two interrupted light patterns.

Electronic circuitry converts each light pattern into a d.c. voltage pulse. Angular displacement of one disk relative to the other produces a phase shift in the pulse patterns. Electronic sensing of the shift produces a constant d.c. output proportional to the phase shift; thus the output is also proportional to shaft torque. Measurement of pulse frequency from one disk is a direct indication of shaft rotational speed.

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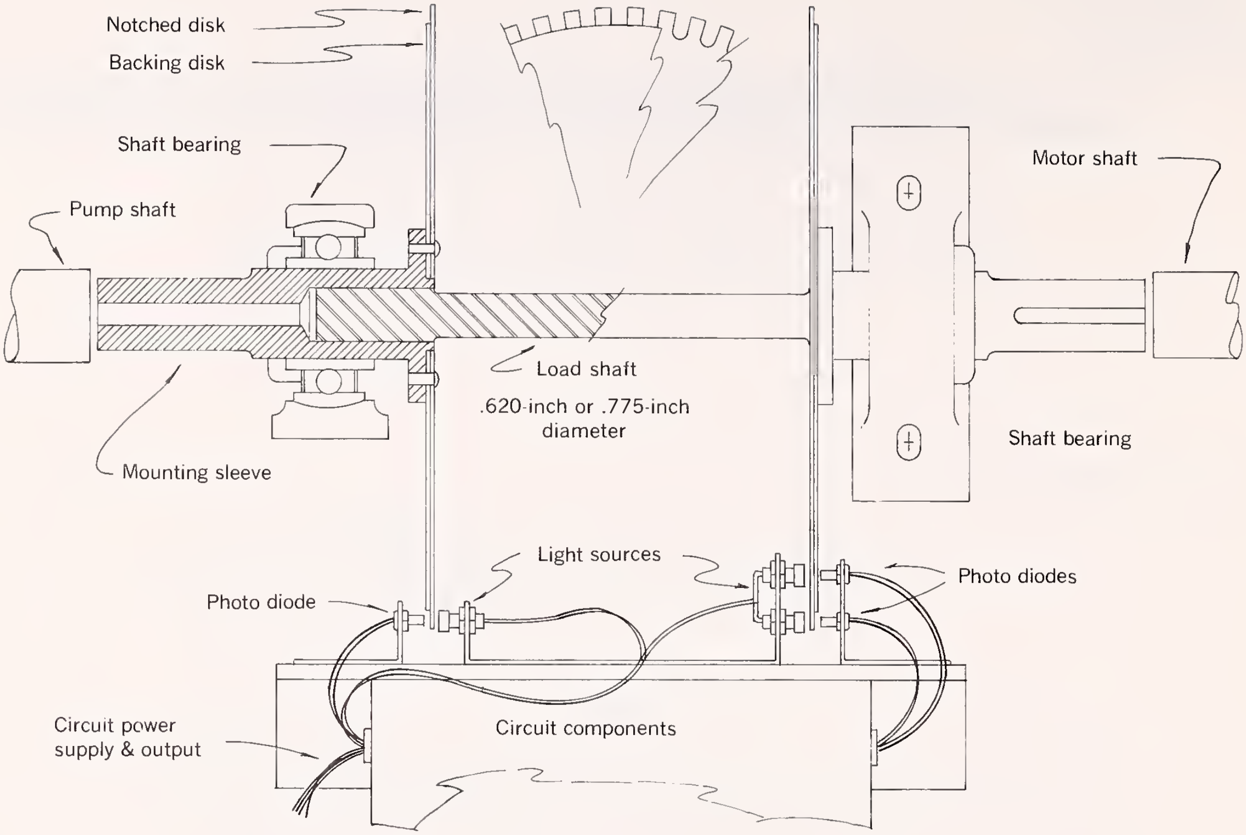


Figure 1.--Torque shaft assembly.

Mechanical Design

The design required a shaft material with sufficient strength to transmit the desired load without permanent deformation, yet sufficiently elastic to enable resolution of small load changes. Aluminum alloy 2024 T4 was selected, although other available metals and metal alloys would have met these requirements. The physical properties of 2024 T4 are as follows:

Yield strength	47,000 p.s.i.
Shear strength	41,000 p.s.i.
Fatigue limit	20,000 p.s.i.
Modulus of elasticity	10.6×10^6 p.s.i.

Load shaft diameter for 6-inch-long shaft was determined using these equations:

$$J = 57.3TL/E_s \phi \tag{1}$$

$$d = \sqrt[4]{32J/\pi} \tag{2}$$

T = load torque in inch-pounds
L = shaft length in inches
E_s = modulus of elasticity of the material
ϕ = angular deformation in degrees
J = polar moment of inertia
d = shaft diameter in inches

Setting 2.5 degrees as the maximum angular deformation, shafts of 0.620-inch and 0.775-inch diameter were selected for load capacities of 500 and 1,000 inch-pounds.

The shear stress on these shafts at design load was determined by equation (3) to be below 11,000 p.s.i.

$$T = Tc/J = 16T/ d^3 \qquad (3)$$

T = shear stress
c = distance to outer fiber of the shaft = $d/2$

Sixty evenly spaced notches were cut into each of the disks. The desired notch size and spacing were obtained by milling the notches 0.250 inch deep in the edge of the 10-inch-diameter disks. Two backup disks (9.550 inches in diameter) were riveted to each 10-inch disk to provide the desired 3-degree square-edge opening and to add stiffness to the disk assembly.

Steel shaft adapters, which were machined to provide bearing support for the load shaft, permit quick exchange or replacement of the shaft and also serve as the mounting for the serrated disks.

The entire shaft assembly rides in pillow bearings firmly mounted to a base assembly. This base assembly, which mounts to the motor and pump base, provides vertical and horizontal adjustment to enable exact alinement of the dynamometer. The stationary lights, photodiodes, and circuitry are mounted on the base assembly.

Electronic Design

The electronic design of the torquemeter can best be followed by referring to figure 2. As the serrated disks interrupt the light to each photodiode, the resistance of these diodes increases. The voltage drop across this changing resistance is amplified and fed into a Schmitt trigger. If the light is shining on the photodiode, the output of the Schmitt trigger will be -8.9 volts. If the light is blocked, the voltage will change to -1.7 volts. As the disks rotate, the output of the Schmitt trigger circuits will be a series of pulses as shown in the oscillograph photograph (fig. 3). Electronic differentiating and clipping the pulses result in impulses, one each time the light is blocked from a photodiode. Similar circuitry is used for each light-photodiode combination to this point.

In operation, as one disk is displaced relative to the other, the impulses created by each circuit are displaced in time. This set of impulses is used to control a bistable multivibrator. The first impulse switches the circuit to a negative voltage level; the lagging impulse returns the multivibrator to a voltage near zero. The result of this switching is a series of pulses; the width of these pulses is dependent on the angular relationship of the two disks (see figs. 4A and 4B). The height of these pulses is constant; therefore, the area under the pulse per unit time is a measure of the torsional load on the shaft. The pulses are integrated by a resistance-capacitance network giving a d.c. voltage output. This voltage is amplified by an operational amplifier to the desired full load level of 1,000 millivolts.

The disks are adjusted on the shaft to give a narrow pulse width from the multivibrator at no-load conditions (figs. 2 and 4). This prevents instability that would result from two pulses arriving at the bistable multivibrator simultaneously. The low output voltage that occurs from this adjustment can be canceled out by a variable resistor in the output circuitry to give a zero output at no-load conditions.

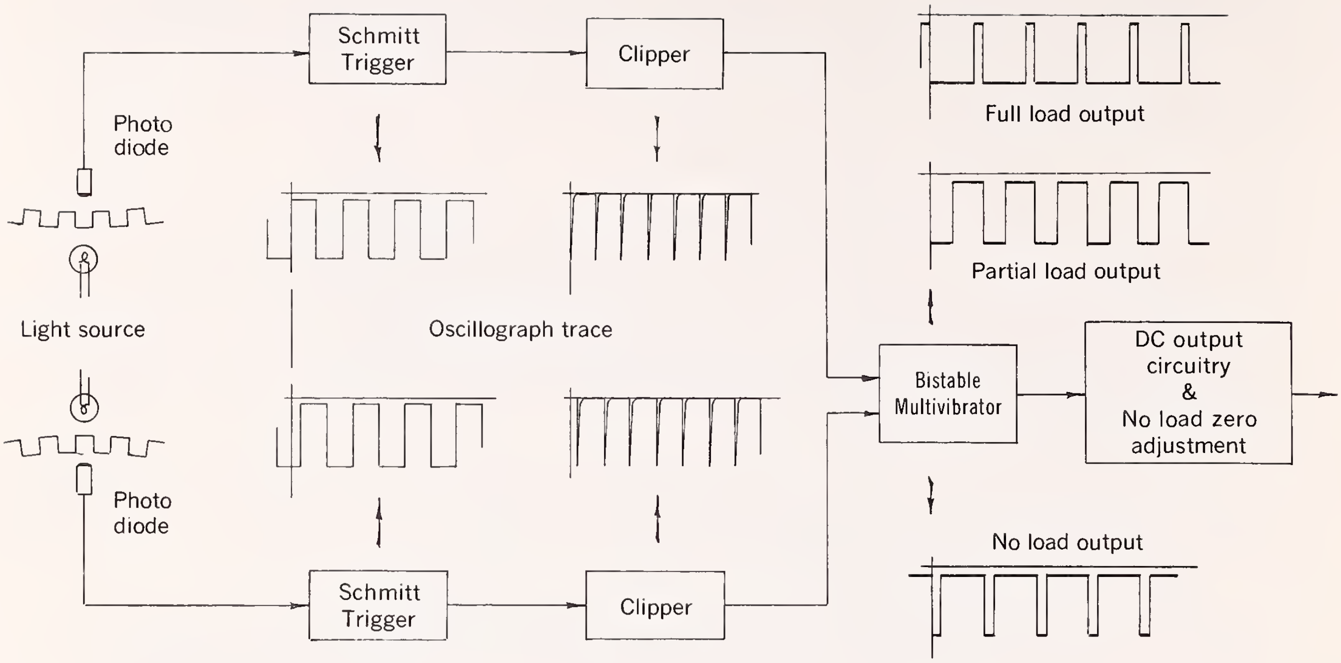


Figure 2.--Schematic of circuit operation.

The rotational speed of the shaft is counted by an electronic frequency counter that simply counts the pulse frequency of one disk. Since the disk has 60 teeth, the pulse count in cycles per second is exactly the same as the speed in revolutions per minute.

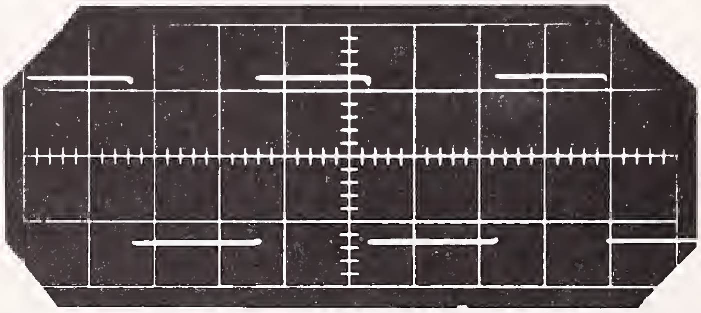


Figure 3.--Schmitt trigger output--each disk.

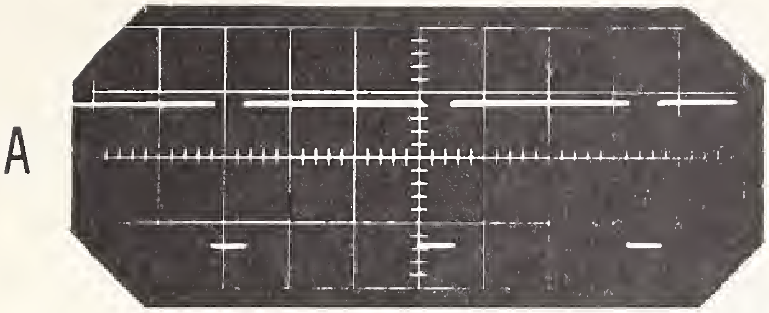
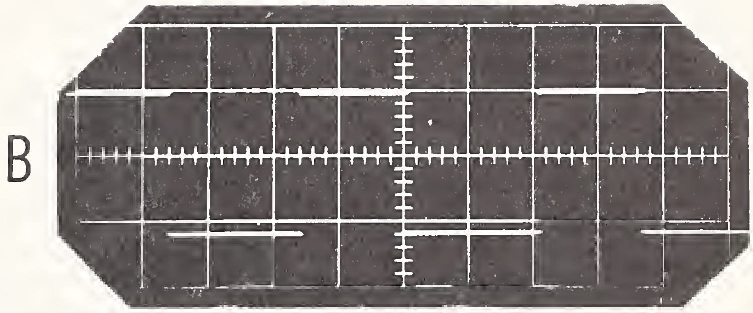


Figure 4.--A, No load multivibrator output; B, partial load multivibrator output.



Calibration

Since the basic principle of operation of the unit is the electronic sensing of the time lag between pulses generated by shaft distortion during rotation, the unit could not be statically calibrated. Thus, the unit was calibrated using a 15-hp d.c. motor as the driving unit and a d.c. dynamometer as the calibrating unit. A diesel-driven d.c. generator was used to supply power to the motor. Motor speed was controlled by the voltage output of the diesel generator and by rheostat control of the motor field current. The electric dynamometer was supplied with constant 220-volt d.c. power. A digital voltmeter and a digital impulse counter were used as readout equipment. The layout of the calibration apparatus is shown in figure 5.

Accurate balance of the dynamometer was checked at all desired speeds before calibration was started. Calibration data were obtained for nominal shaft speeds of 800, 1,000, 1,200, and 1,400 r.p.m. An initial no-load reading was obtained when the unit was operating at the desired speed while disconnected from the load. The unit was then connected to the dynamometer. Weights were placed on the dynamometer balance arm; calibration was achieved by adjusting the field current of the dynamometer so as to cancel the external load. As each increment of applied load was balanced, the load, shaft speed, and voltage output were recorded. At the conclusion of each run, the no-load reading was again determined.

During the first calibration run on the small shaft, the shaft was accidentally overloaded. This unknown overload permanently twisted the shaft approximately 40 degrees before a circuit breaker tripped and relieved the load. As no other damage was apparent, the disks were repositioned to give the desired no-load output, and the calibration procedure was carried out.

Figure 6 presents a typical graph of shaft torque versus voltage output for the 0.650-inch-diameter shaft.

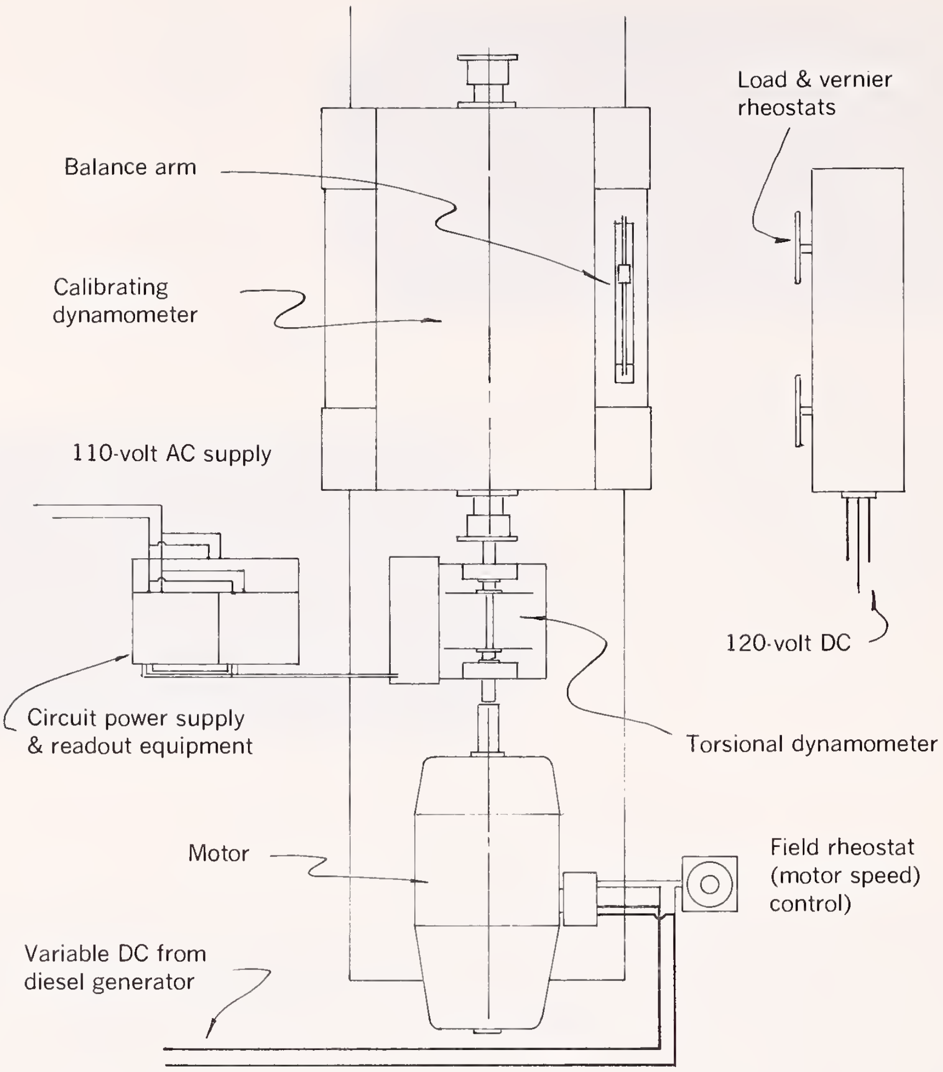


Figure 5.--Calibration equipment.

The 0.775-inch shaft was calibrated in the same manner. Care was taken to ensure that this shaft was not overloaded. Figure 7 presents typical results of these calibration runs.

In view of the excellent results obtained for the small shaft, the results obtained for the large shaft were considered unsuitable because of the excessive spread of calibration points. The only differences between the shafts were in size and state of material deformation.

A change in shaft size should affect only the total load capacity and not the repeatability of the stress-strain relationships. The state of material deformation could affect the stress-strain characteristics.

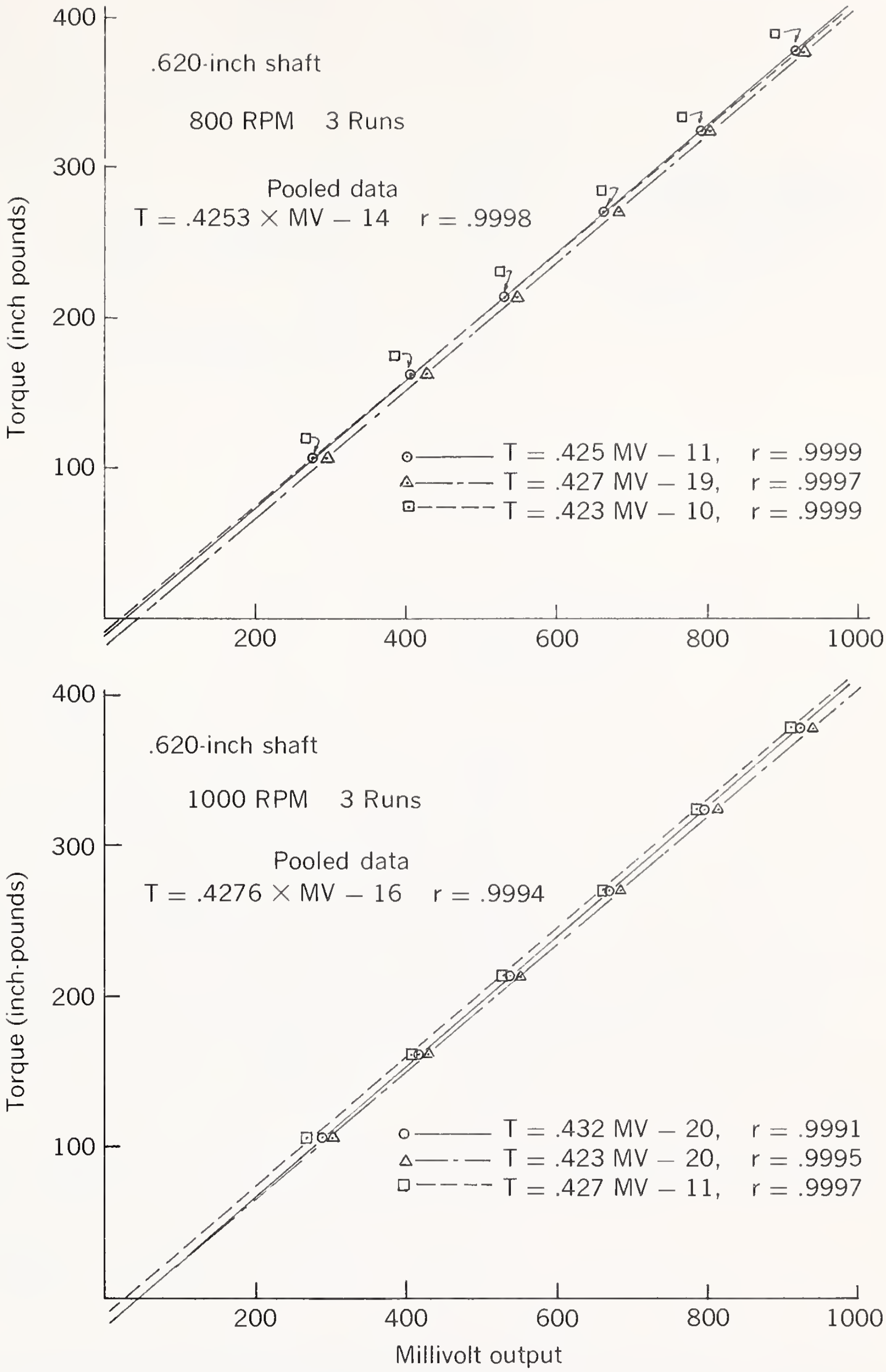
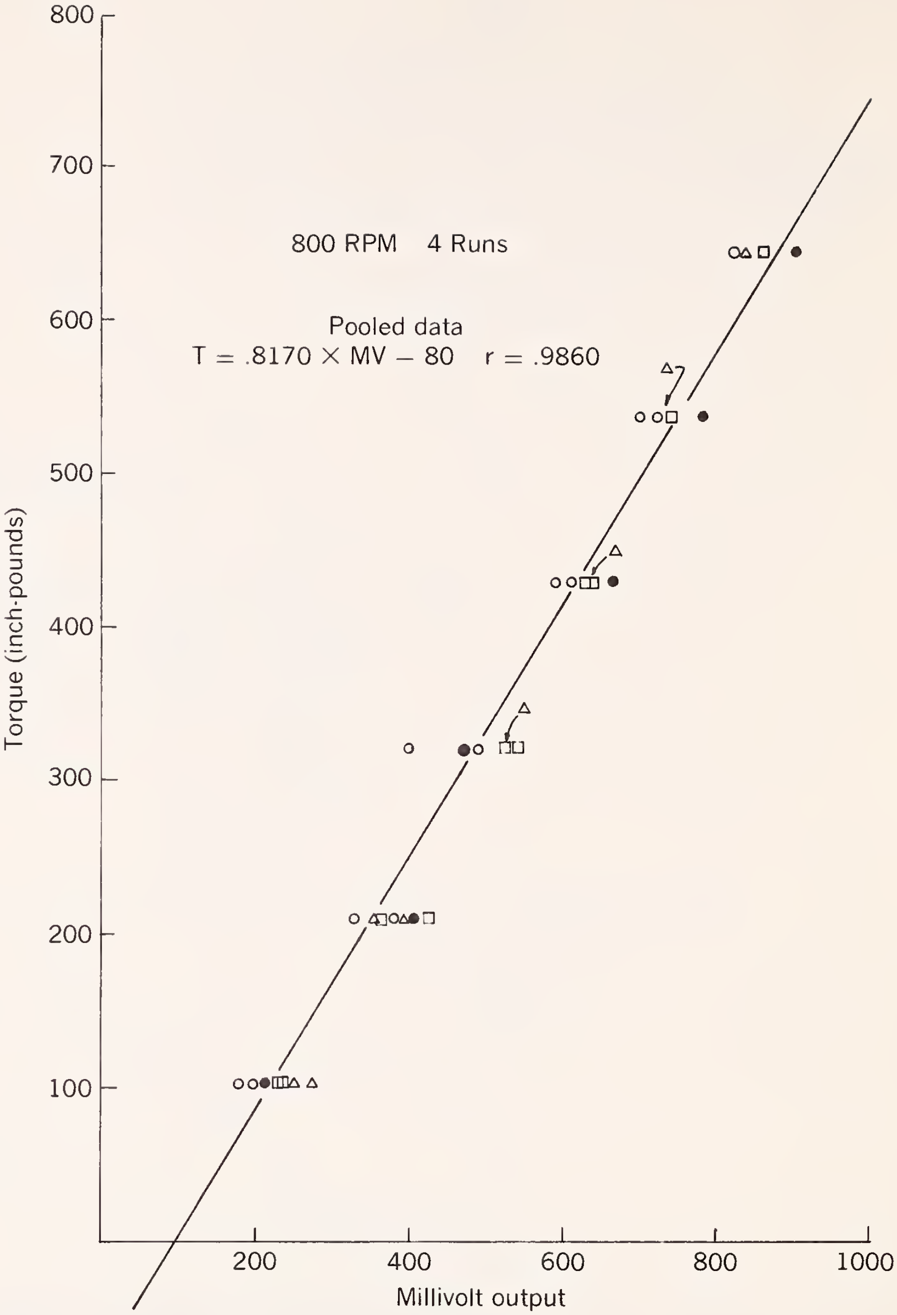


Figure 6.--Dynamometer output vs. torque.

Most aluminum alloys do not have a clearly defined elastic limit, and it is possible that stresses caused by starting torque or dynamometer loading may have exceeded the elastic limit even though the calculated stress was below 11,000 pounds per square inch.

Any permanent deformation would cause an increase in the voltage output of the photodiode circuitry. Any later relaxation of the shaft at lower loads would cause a decrease in voltage output.

Figure 7.--Dynamometer output vs. torque.



The unintentional deformation of the first shaft apparently stress-hardened the material and raised the elastic limit to a level high enough to preclude any further deformation at the starting speeds under design loads. This idealized condition is shown graphically in figure 8.

Improvement of the repeatability of the stress-strain characteristics at or near the elastic limit could be achieved by overloading the material. Therefore, we intentionally deformed the large shaft by mounting it between lathe centers and manually turning the headstock until the total deformation was approximately 40 to 45 degrees. The shaft was then recalibrated. Figure 9 presents the results of this calibration; a reduction in the spread of data is clearly evident.

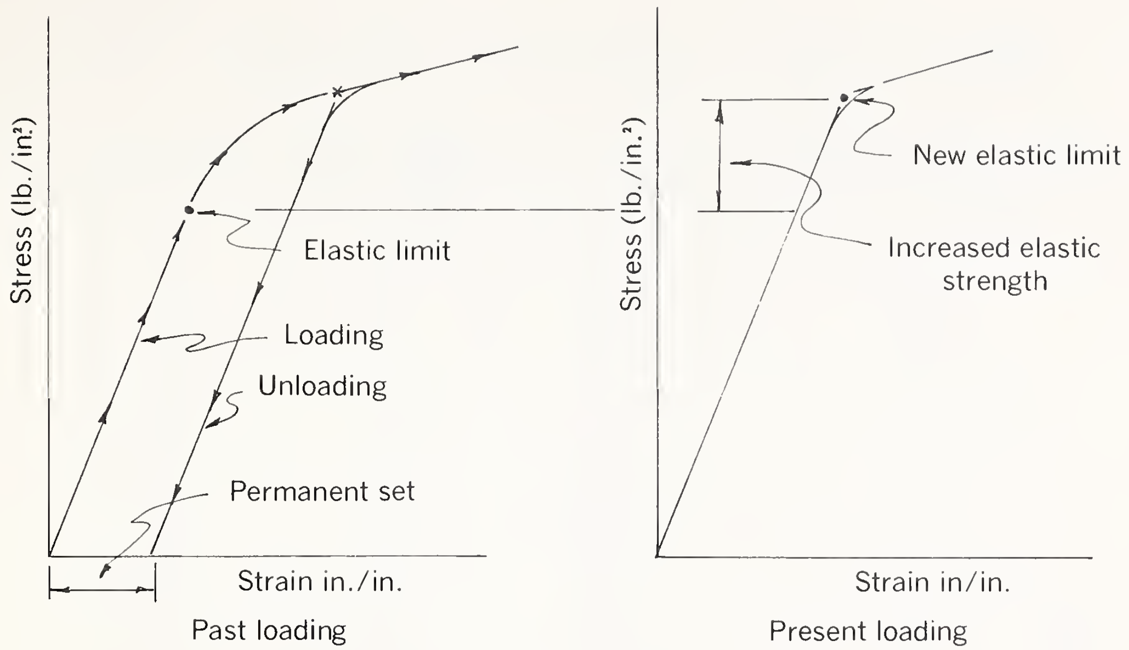


Figure 8.--Idealized stress-strain diagram.

In-Service Evaluation and Conclusions

The unit was installed with a quick-disconnect flexible coupling on the pump side to provide ease in checking and adjusting the no-load output.

Initial tests indicated some temperature sensitivity during the first few minutes of each test period, probably due to heat generated by the motor or the dynamometer circuitry. A warmup period of approximately 5-10 minutes was necessary to provide a stable temperature at which repeatability well within the desired ±1 percent of full-load output was obtained.

Some drift in the no-load output signal was occasionally noticed after long testing periods of 30 minutes or more. The cause of this drift was not determined, but it was avoided by interrupting such long tests and checking and adjusting the no-load output signal during the run.

Table 1 presents typical data on pump performance results obtained during the testing program.

The photoelectric principle is very effective in detecting slight angular displacement caused by torsional loading of a rotating shaft.

The circuitry of the unit is temperature sensitive to some degree; the unit should be operated for a short warmup period, and used in an area that remains at a relatively constant temperature during a testing sequence. Periodic checks of conditions of no load should be made to insure an accurate indication of voltage change due to shaft loading.

Circuitry changes, using electronic components of greater temperature stability, would undoubtedly be possible to reduce or eliminate the temperature fluctuations should higher precision be desired for similar investigations.

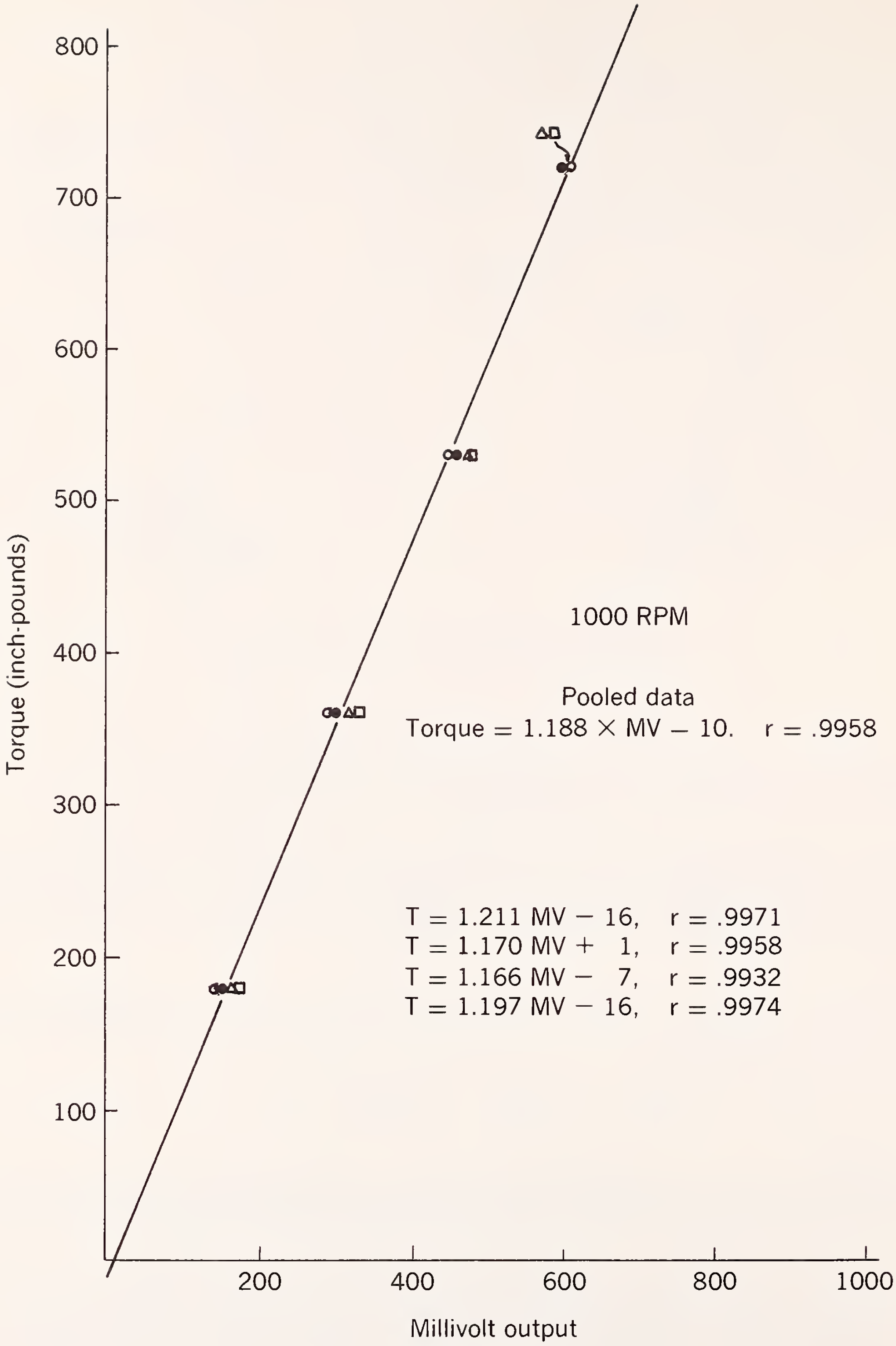


Figure 9.--Dynamometer output vs. torque.

Table 1.--Preliminary test data at nominal pump speed--1,150 r.p.m.[1]

Pump speed	Flow rate	Torque output	Differential pump pressure
R.p.m.	G.p.m.	Millivolts	Inches of mercury
1,155	500	249	25.2
1,159	450	239	27.3
1,153	400	224	28.4
1,156	350	212	30.1
1,150	300	198	31.1
1,154	250	182	33.0
1,156	200	166	34.1
1,150	150	149	35.1
1,148	200	164	33.8
1,156	250	183	33.1
1,154	300	198	31.3
1,153	350	210	29.9
1,150	400	224	28.3
1,149	450	236	26.7
1,149	500	245	24.9

[1] Initial no-load torque reading, 0 millivolts; final no-load torque reading, +2 millivolts.

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